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ASTRONOMY AND ASTROPHYSICS

Removal of the calcium underabundance in cool metal rich Galactic disk dwarfs*

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Abstract. An apparent Ca underabundance for cool metal rich disk dwarfs was derived by Feltzing & Gustafsson (1998). This was suggested to be a NLTE effect, following the prediction by Drake (1991). New NLTE calculations with MARCS atmospheres and opacities show that deviations from LTE are very small and can *not* explain the underabundance. It is shown that the underabundance was primarily due to erroneously calculated atomic line broadening parameters (van der Waals broadening). Part of the underabundance was also due to the decision not to change photometrically determined stellar parameters to satisfy the Fe I excitation balance.

Key words: Physical data and processes:atomic data–stars:abundances–stars:late type

1. Introduction

Calcium, being one of the so called α-elements, is believed to be produced in SNII, exploding massive stars. Due to the early start of such events in the Galaxy as compared to the other stellar nucleosynthesis sites SNIa and AGB stars, old (metal poor) stars are usually rich in Ca compared to Fe as compared to the corresponding solar Ca/Fe ratio (e.g McWilliam et al., 1995; Chen et al., 2000). For metal rich stars the Ca/Fe trend seems to level out at the solar value. A considerable scatter was found for 48 metal rich disk dwarfs by Feltzing & Gustafsson (1998). As a mean [Ca/Fe]~ 0, but for the cool dwarfs a significant underabundance was derived. To examine this, I observed 10 cool disk dwarfs with ESO CAT/CES in Nov-Dec 1995. The underabundance in Ca for K-dwarfs was suspected to be caused by overionization, as predicted by Drake (1991). A MULTI (Carlsson, 1986) NLTE investigation of this with a new Ca atom model was therefore performed by Thorén (2000).

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* Based on observations made at ESO, La Silla

Table 1. Observed stars and their photometrically determined parameters. The microturbulence parameter was set to 1 km/s for all models.

Star	$T_{\rm eff}$ (K)	log g	[M/H]
HD 12235	5971	4.18	0.15
HD 21197	4457	4.59	0.13
HD 23261	5132	4.44	0.06
HD 30501	5174	4.54	0.13
HD 31392	5390	4.29	0.06
HD 32147	4625	4.57	0.17
HD 42182	4917	4.54	0.25
HD 61606	4833	4.55	0.06
HD 69830	5484	4.34	0.10
HD 213042	4560	4.58	0.06
The Sun	5780	4.44	0.00

2. Observations and analysis

The observational data and the LTE analysis are presented in detail in a separate paper with a wider scope (Thorén and Feltzing, 2000). The stars observed and the parameters used in the models are presented in Table 1. The LTE line profiles computed by the Uppsala synthetic spectrum code SPECTRUM agreed well with the observed spectra. With a new Ca model atom for the code MULTI it appeared that NLTE effects for Ca in the cool dwarfs in the sample actually were very small (Thorén, 2000). The recent MARCS atmospheres (Asplund et al., 1997) have a higher, more realistic amount of UV metal line blocking than the models used by Drake (1991). This increases the opacity and decreases the non-local ionizing radiation field. Except in the line cores no strong NLTE effects could be seen, rather the Ca/Fe ratio appeared solar, as for the hotter stars in Feltzing & Gustafsson (1998). The suggested underabundance, if not real, had to have a different origin.

3. Atomic line data

The lines used in this analysis are presented in Table 2. They were selected from the VALD database (Piskunov et al., 1995). Most oscillator strengths of the lines used in the analysis were modified, to fit our solar observations. VALD provides oscillator strengths typically correct to the order of magnitude. The van der Waals broadening parameters for lines used in the analysis were also changed. For Ca lines the van der Waals broadening width in terms of $\delta\Gamma_6$ factors (being the corrections to the classical Unsöld value) calculated from lab measurements by Smith (1981) are used, except for the 6798 Å line for which no $\delta\Gamma_6$ value was available. However, this line is very weak and is not affected significantly by pressure broadening. Its broadening was calculated according to Barklem & O'Mara (1997). For Fe I lines the damping was calculated according to Anstee & O'Mara (1995) and Barklem & O'Mara (1997) for the lines in Table 2 marked with asterisks. For the remaining Fe I lines the $\delta\Gamma_6$ factor had to be used.

When the atomic line data for the project were examined, the explanation was highlighted. The Uppsala code EQWIDTH had been used for the analysis in Feltzing & Gustafsson (1998). This code uses a correction factor $\delta\Gamma_6$ as input for atomic line broadening by H atoms. To get the broadening the factor is multiplied with the classical Unsöld broadening value. This factor is typically ~ 2. The Ca atomic line parameters used by Feltzing & Gustafsson (1998) and Thorén (2000) are both taken from Smith (1981). The Ca lines $\delta\Gamma_6$ factors were, however, erroneously calculated in Feltzing & Gustafsson (1998), causing the line broadening to be much too large. In the cool dwarfs the overall line strength is larger than in the hotter ones. For lines with equivalent widths increasing beyond 50 mÅ this parameter soon becomes very important, because it brings the line out of the saturated region on the curve of growth faster. This means that a model line is too strong for any given abundance, forcing a reduction of the abundance in order to satisfy the measured equivalent width.

Since Feltzing & Gustafsson (1998) used equivalent widths, rather than synthetic spectra, the effect was not noticed until it showed up as an apparent underabundance for Ca in the cool dwarfs. Since such a NLTE effect had already been predicted (Drake, 1991), this was suggested to be the cause. Because of this it was decided to make the new K dwarf observations and a new MULTI analysis for Ca. The Ca NLTE properties of cool metal rich dwarfs will be discussed in Thorén (2000).

The abundances were obtained in the following way: First synthetic spectra were fitted with SPECTRUM to the observed spectra. The atmospheric model parameters used were those determined with photometric Strömgren calibrations for Pop I F-G dwarfs, presented by Olsen (1984). The Strömgren colors were obtained from the catalogues in Olsen (1994) and Olsen (1995).

The equivalent widths of the fitted synthetic lines to be used in the abundance analysis were exported from the fitted spectra. These equivalent widths were then used as measured ones from the observed spectra and used as

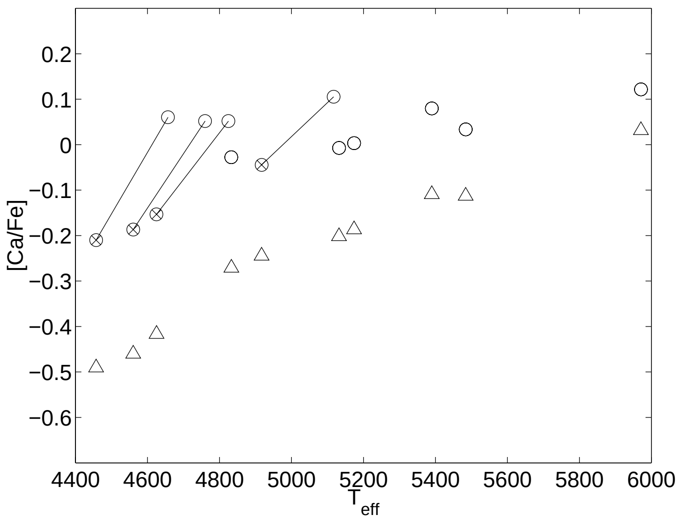

Fig. 1. △ : Ca abundance pattern for 10 dwarfs with old $\delta\Gamma_6$ values, ◯ : abundances with new $\delta\Gamma_6$ values. ⊗ : abundances for HD21197, HD32147, HD42187 and HD213042 before $T_{\rm eff}$ adjustment. ◯ : abundances after $T_{\rm eff}$ adjustment. Lines connecting different symbols indicate identical stars.

input into the code EQWIDTH (which was used in the analysis of Feltzing & Gustafsson (1998)). The lines used in the analysis are presented in Table 2.

Figure 1 shows the difference in abundance pattern for the old and new calculated values of Γ_6. Triangles represent abundances determined with the values in Feltzing & Gustafsson (1998), circles represent abundances with corrected Γ_6 values. As seen in the Fig. 1 there remains an increasing trend in [Ca/Fe] with increasing temperature after the damping treatment correction. This effect is reduced to virtually zero when the photometric effective temperatures are adjusted, according to Thorén & Feltzing (2000), until Fe I lines of different excitation energy give similar iron abundances. Four of the stars required such changes. Their Ca abundances before (⊗) and after (◯) temperature adjustments are shown in figure 1. The need for $T_{\rm eff}$ changes is illustrated for one of the objects in Fig. 2. HD32147 needed a positive temperature correction of 200 K, which also raised the Ca abundance by +0.20 dex.

4. Summary

Changing Γ_6 to the 'true' value reduces the underabundance by 0.3 dex for the coolest stars in this sample. This solves the major part of the underabundance problem.

The photometric effective temperatures adopted by Feltzing & Gustafsson (1998) lead in some cases to severe trends in the abundances derived from Fe I lines with different excitation energy. Modifications of these $T_{\rm eff}$ values dramatically decrease this abundance scatter and also

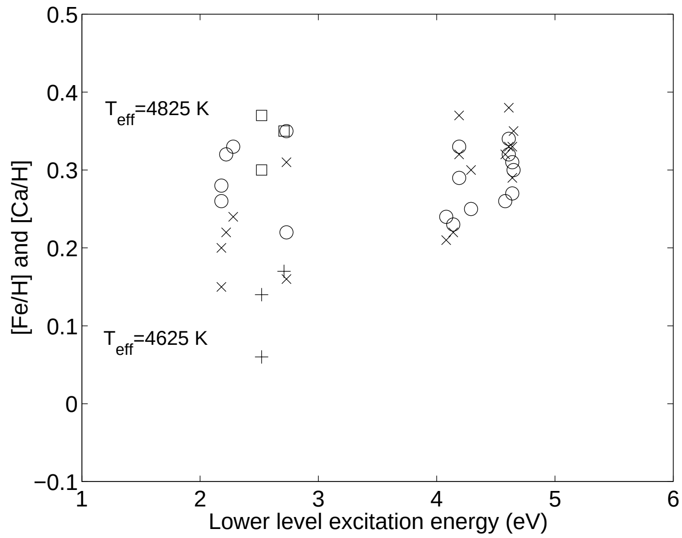

Fig. 2. Abundances for different Fe and Ca lines of HD32147. × and + : Fe and Ca abundances before temperature correction. ○ and □ : Fe and Ca abundances after temperature correction.

modify the Ca abundances to values observed in hotter stars of similar metallicity.

The results in this work and in the forthcoming paper (Thorén and Feltzing, 2000) indicate that LTE abundance analysis is indeed useful even for cool metal rich dwarfs, increasing the number of objects available for studying the chemical evolution of the Galaxy.

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Table 2. Line data used in this investigation. Astrophysical $\log gf$ values were determined from ESO CAT-CES solar flux observations. Asterisks indicates that the pressure broadening was calculated according to Anstee & O'Mara (1995) and Barklem & O'Mara (1997) and that $\delta\Gamma_6$ was not used.

Wavelength (Å)	$\chi_{\rm low}$ (eV)	$\log gf$	$\delta\Gamma_6$	Γ_{rad} (rad s^{-1})
Ca I				
6166.439	2.521	-1.142	1.64	1.858E+07
6455.598	2.523	-1.290	0.71	4.645E+07
6798.467	2.709	-2.520	*	1.941E+07
Fe I				
6151.618	2.176	-3.379	*	1.549E+08
6157.728	4.076	-1.320	*	5.023E+07
6159.378	4.607	-1.970	*	1.919E+08
6165.360	4.143	-1.554	*	8.770E+07
6173.336	2.223	-2.920	*	1.671E+08
6180.204	2.727	-2.686	1.40	1.469E+08
6430.846	2.176	-2.006	1.40	1.648E+08
6436.407	4.186	-2.410	1.40	3.041E+07
6481.870	2.279	-2.984	1.40	1.549E+08
6756.563	4.294	-2.750	*	7.345E+07
6786.860	4.191	-1.850	1.40	1.986E+08
6804.001	4.652	-1.546	1.40	1.758E+08
6804.271	4.584	-1.813	1.40	5.236E+07
6806.845	2.727	-3.110	1.40	1.021E+08
6810.263	4.607	-0.986	1.40	2.301E+08
6820.372	4.638	-1.120	1.40	2.218E+08
6828.591	4.638	-0.820	*	2.301E+08

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